

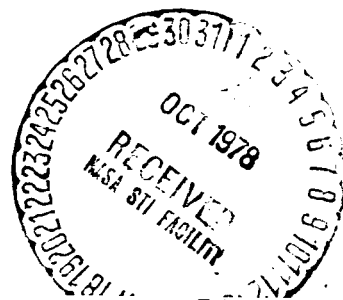
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A COMPUTER VERSION OF THE U. S. STANDARD ATMOSPHERE, 1978

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16. ABSTRACT A computer version of the recently published U. S. Standard Atmosphere, 1976, has been developed. The computer program has been developed in modular form for easy incorporation into the user's program and for easy modification for specialized uses. Because of the lack of atmospheric variability, the US 76 will find limited use in aerospace research. However, it will become the standard against which all other atmospheric models will be measured.			
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I. INTRODUCTION

The U. S. Standard Atmosphere, 1976 (Ref. 1) has recently been published and represents the most current thought on the definition of the atmosphere from the surface to 1000 km. The representation is that of a steady-state idealized atmosphere under moderate solar activity. This report documents a computer version of this Standard Atmosphere (US 76).

The computer version of US 76 was designed to be a flexible tool which could be modified to the user's needs with minimum effort or knowledge of the mechanics of the program. For this purpose the program is segmented into three distinct altitude regions which represent separate calculations. The program can be used as a single package or may be easily divided into pertinent subprograms for specialized use.

The computer program has been tested and will reproduce the U.S. Standard Atmosphere, 1976, table values of each parameter to at least three significant figures. The least accurate values arise from calculations requiring numerical integrations, and these could be improved by decreasing the tolerance allowed in the numerical integrations.

Comparison of the US 76 with other recent atmospheric models reveals a reversal of the trend to attempt to reproduce the variability of the atmosphere. It has been noted that the structure of the current model lends itself to the same type of modifications found in the U. S. Standard Atmosphere Supplements, 1966 (US 66) which were made to the U. S. Standard Atmosphere, 1962 (US 62). It would appear reasonable to propose that such modification to the computer program presented here would be the most natural method for including the variability of the upper atmosphere within the context of US 76.

Because of the lack of representation of atmospheric variability usage of this program is somewhat limited. The principal uses of this program are considered to consist of three types of user requirements. First, this program provides a current and a well documented atmosphere model which could be used by researchers requiring representative values for given atmospheric parameters in their programs. Second, for comparisons with other atmospheric models or atmospheric measurements this program could be used for the production of graphical comparisons. Third, the program could be used as a substitute for a more complex atmospheric model for program development and checkout.

Much of the code for the US 76 computer program was developed and checked out with the use of a programmable hand calculator. Consequently, it would be a simple extension of the current work to optimize the instruction codes and storage requirements of the larger program for use on such calculators. One such program is already in use, the calculation of atmospheric density from the earth's surface to 32 km has been reduced to a 56 step program requiring only 15 storage locations on one such calculator. With card input available on these calculators it would appear that a "portable" U. S. Standard Atmosphere 1976, could easily be produced.

The discussion of the US 76 computer program introduced in this section is amplified in the sections which follow. A detailed description of the computer program is presented in Section II. In Section III the use of the program is described along with methods to specialize the program to the user's needs without modifying the code. In Section IV the US 76 model is compared with other current atmospheric models and some suggestions are given as to how the program might be modified to account for some atmospheric variability. Finally, the results are summarized in Section V. A complete program listing is provided in the Appendix.

II. PROGRAM DESCRIPTION

The U. S. Standard Atmosphere, 1976 (US 76) is based on an empirical temperature profile for 45N during moderate solar activity (Ref. 1). This temperature profile is shown in Figure II-1 along with that for the US 62. Below 86 km the pressure or density, is obtained from the integration of the hydrostatic equation; above 86 km density is obtained from the intergration of the diffusion equation for each individual atmospheric constituent. The remaining state variable, either pressure or density, is obtained from the other two using the gas law for an ideal gas.

The temperature below 86 km, as shown in Figure II-1, is specified by segments which are linear functions of geopotential altitude. Between 86 km and 91 km the atmosphere is assumed to be isothermal and between 110 km and 120 km the temperature is a linear function of altitude. Between 91 km and 110 km the temperature is represented by a section of an ellipse. Above 120 km the temperature increases exponentially and is asyptotic to 1000°K . The altitude described is measured along a line perpendicular to a geopotential surface and the altitude is taken to be zero along the geopotential surface at mean sea level (see Ref. 12, pp 217-219). Reference 1 should be consulted for all questions concerning the definition of parameters.

The US 76 subroutine is divided by temperature regions. Figure II-2 shows the structure of the subroutine. Subroutine US 76 calls one of three subroutines, LDEN, MDEN, or NDEN, depending upon the altitude designated by the calling program. These three subroutines will calculate the density, pressure and temperature within these given altitude ranges using the supporting subroutines and functions shown. The subroutine LDEN has no actual supporting routines. The subroutines AUX1 and AUX2 are called to calculate other parameters in the 0 to 86 km altitude range, such as mean collison frequency and dynamic viscosity. Thus, these routines are not called by LDEN but by US 76.

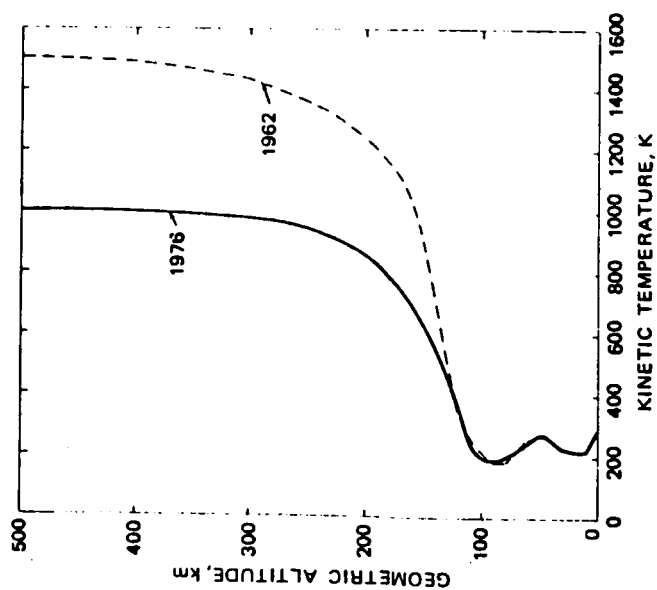
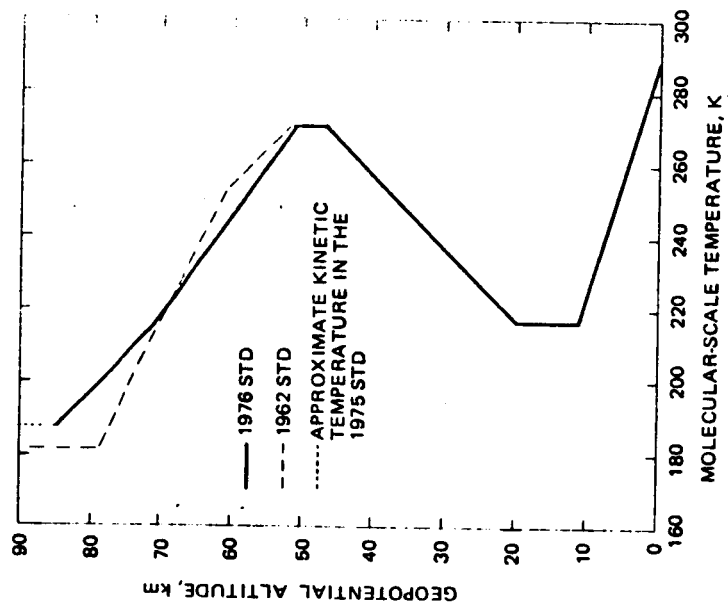


Figure II-1. (A) Kinetic Temperature as a Function of Geometric Altitude.
 (B) Molecular - Scale Temperature as a Function of Geopotential Altitude. (Ref. 1)

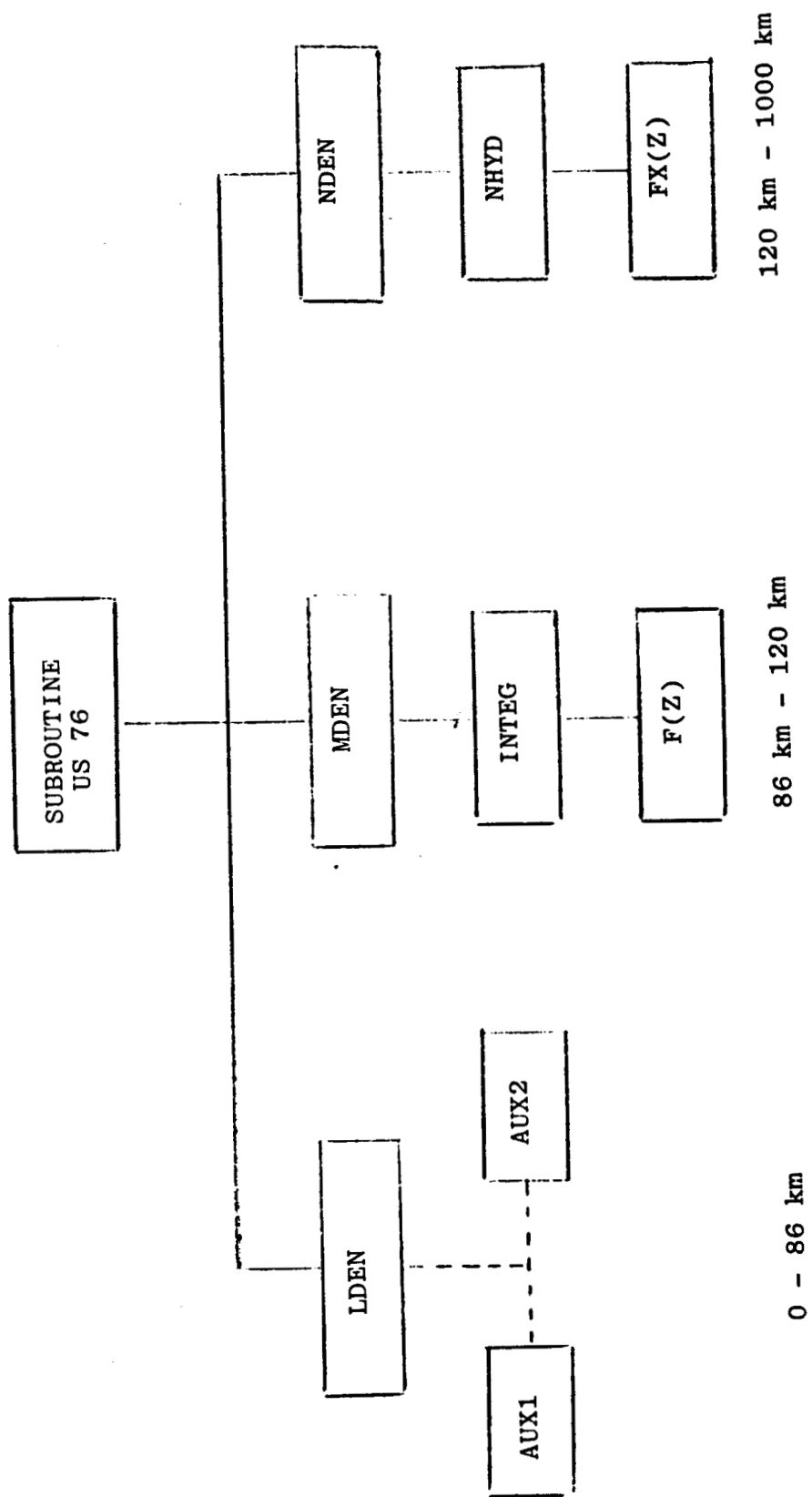


Figure II-2. Subroutine US 76

The remaining portion of this section will be devoted to descriptions of each routine. The analytical development of the equations upon which this program is based are developed in Reference 1. Because of the nature of this report it is assumed that the reader is familiar with this analytic development or has ready access to Reference 1. Thus, the analytic development of equations will not be repeated here and equations may be presented without a complete description. Input and output parameters to these subroutines will be described in Section III.

2.1 SUBROUTINE US 76

This routine is the basic calling routine for the U. S. Standard Atmosphere, 1976. As such, it determines that the altitude requested by the calling program is within the appropriate limits;

$$0 \leq Z \leq 1000 \text{ km}$$

otherwise, all returned values will be zero. Also, this routine ascertains what information has been requested by the calling program and returns that information (see Section III).

2.2 SUBROUTINE LDEN

Subroutine LDEN computes the temperature, density and pressure in the region between 0 and 86 km. The temperature is computed from the hydrostatic equation and the state equation using tabulated values of density for each temperature interval. The pressure is calculated from the state equation.

2.2.1 Subroutine AUX1

Subroutine AUX1 does not support LDEN but calculates the mean air particle speed, the mean free path, the mean collision frequency and the speed of sound below 86 km. The formulae used in this routine are given in Reference 1.

2.2.2 Subroutine AUX2

Subroutine AUX2 does not support LDEN but calculates the dynamic and kinematic viscosities as well as the thermal

conductivity of the atmosphere below 86 km. The formulae used in this routine are given in Reference 1.

2.3 SUBROUTINE MDEN

Subroutine MDEN computes the temperature, density and pressure in the region between 86 and 120 km. In this region the temperature is isothermal between 86 and 91 km, an elliptical function of altitude between 91 and 110 km, and a linear function of altitude between 110 and 120 km. The density is computed from the diffusion equation in the form

$$n_i(Z) = n_i(Z_0) \frac{T(Z_0)}{T(Z)} \exp \left\{ - \int_{Z_0}^Z \left[f(Z) + \frac{v_i}{D_i + K} \right] dZ \right\} \quad (1)$$

where the subscript indicates the atmospheric constituent. The term $v_i/(D_i + K)$ represents a diffusion transport which is parameterized to account for actual constituent distribution between 86 and 120 km. This term can be written as

$$\frac{v_i}{D_i + K} = \frac{dG(Z)}{dZ}$$

so that

$$n_i(Z) = \left[n_i(Z_0) \frac{T(Z_0)}{T(Z)} e^{-G(Z)} \right] \exp \left\{ - \int_{Z_0}^Z f(Z) dZ \right\} \quad (2)$$

The integral in Equation (2) cannot be solved analytically in this region and must be evaluated numerically. This evaluation is performed by the supporting routines INTEG and F(Z).

The temperature, density, the constituent number density and the pressure are all evaluated in MDEN. The density is computed from the number densities of the constituents which are easily obtained once the integral in Equation (2) is evaluated.

2.3.1 Subroutine INTEG

Subroutine INTEG evaluates the integral

$$U = \int_{Z_0}^{Z_T} f(Z) dZ$$

using Simpson's 1/3 Rule. Because the calculations made in this routine are not described in Reference 1, a more complete description of this routine will be given in the following paragraph.

Simpson's Rule approximates the function U by

$$U_k = \frac{h}{3} (f_0 + 2f_1 + 4f_2 + 2f_3 + 4f_4 + \dots + 4f_{k-1} + f_k)$$

where h is the altitude interval between terms, $h = Z_k - Z_{k-1}$.

In programming Simpson's Rule no redundant calculations were allowed. Thus, the calculation proceeded in the following manner where $h = \frac{1}{2} (Z_T - Z_0)$

$$I_0 = f(Z_0) + f(Z_0 + 2h)$$

$$I_1 = f(Z_0 + h)$$

$$I_2 = f(Z_0 + h/2) + f(Z_0 + 3h/2)$$

$$I_3 = f(Z_0 + h/4) + f(Z_0 + 3h/4) + f(Z_0 + 5h/4) + f(Z_0 + 7h/4)$$

$$\vdots \quad \quad \quad \vdots \quad \quad \quad \vdots \quad \quad \quad \vdots \quad \quad \quad \vdots$$

$$I_k = f(Z_0 + \frac{h}{2^{k-1}}) + f(Z_0 + \frac{3h}{2^{k-1}}) + \dots$$

Then take

$$J_1 = I_0 + 4I_1$$

$$J_2 = J_1 - 2I_1 + 4I_2$$

$$J_3 = J_2 - 2I_2 + 4I_3$$

$$\vdots \quad \quad \quad \vdots \quad \quad \quad \vdots$$

$$J_k = J_{k-1} - 2I_{k-1} + 4I_k$$

From which the estimates U_k are obtained

$$\begin{aligned} U_1 &= m J_1 & \text{where: } m &= h/3 \\ U_2 &= (m/2) J_2 \\ U_3 &= (m/4) J_3 \\ &\vdots & & \\ U_k &= (m/2^{k-1}) J_k \end{aligned}$$

As programmed the estimate U_k is accepted if

$$\left| \frac{U_k - U_{k-1}}{U_k} \right| < \epsilon ,$$

where ϵ is a predetermined constant, or it is terminated if k exceeds some given limit. In the program presented in the Appendix

$$\text{or} \quad \left| \frac{U_k - U_{k-1}}{U_k} \right| < 0.0001$$

$$k = 10$$

terminates the numerical integration and U_k is returned as the final estimate. These values cannot be changed without modifying the code.

2.3.2 Function F(Z)

The function integrated in INTEG is

$$f(Z) = \frac{g}{R^* \cdot T} \cdot \left(\frac{D_i}{D_i + K} \right) \cdot \left[m_i + \frac{M \cdot K}{D_i} + \frac{\alpha_i \cdot R^*}{g} \cdot \frac{dT}{dZ} \right] \quad (3)$$

which is Eq (36) of Reference 1. In this equation the molecular diffusion coefficient D_i , the eddy diffusion coefficient K , the mean molecular weight M , the acceleration due to gravity g , the temperature T , and the temperature gradient dT/dZ are functions of altitude. The gas constant R^* , the molecular weight of the constituent M_i and the thermal diffusion coefficient α_i are constants.

The acceleration of gravity, the eddy diffusion coefficient, the temperature and temperature gradient are simple functions of altitude and can be immediately evaluated from the equations given in Reference 1. The mean molecular weight is taken to be 28.9644 g/mole between 86 and 100/km; above 100 km the mean molecular weight is taken to be 28.0134 for the calculation of the number densities of molecular nitrogen, atomic oxygen and molecular oxygen. Reference 1 suggests that the number densities of Argon and Helium be evaluated above 100 km using a mean molecular weight based on the number densities of nitrogen and atomic and molecular oxygen at the given altitude. Since the mean molecular weight based on the three dominant constituents is nearly the same as the actual mean molecular weight, the latter was approximated between 100 km and 120 km by a polynomial

$$m = b_0 + b_1Z + b_2Z^2 + b_3Z^3 + b_4Z^4$$

This value was used only in the calculation of Argon and Helium above 100 km.

The molecular diffusion coefficient is dependent upon the total number density. It was impractical to compute this for every altitude interval; consequently, the molecular diffusion coefficient was approximated by a fourth order polynomial

$$D_i = c_{i,0} + c_{i,1}Z + c_{i,2}Z^2 + c_{i,3}Z^3 + c_{i,4}Z^4$$

2.4 SUBROUTINE NDEN

Subroutine NDEN calculates the temperature, density and pressure above 120 km. This routine also calculates the number densities of all constituents except hydrogen.

In the region above 120 km the eddy diffusion coefficient K vanishes. Thus, the function $f(Z)$ reduces to

$$f(Z) = \frac{gM_i}{R^*T} + \frac{\alpha_i}{T} \frac{dT}{dZ} \quad (4)$$

The functional form of the temperature with altitude allows the integral

$$U = \int_{Z_0}^Z f(Z) dZ \quad (5)$$

to be evaluated analytically.

2.4.1 Subroutine NHYD

Above 150 km the hydrogen number density is computed in subroutine NHYD. Above 500 km the hydrogen number density is computed from Eq (1) with $f(Z)$ defined by Eq (4). However, for hydrogen $G(Z) = 0$ in Eq (2) and the base of the integral in Eq (5) is taken as $Z_0 = 500$ km rather than 120 km. Between 150 km and 500 km, Eq (1) is modified so that

$$n(Z;H) = \left[n(Z_0;H) - \int_{Z_0}^Z \frac{\phi}{D(H)} \left(\frac{T(Z)}{T(Z_0)} \right) \cdot e^{\tau} dZ \right] \cdot \left(\frac{T(Z_0)}{T(Z)} \right) \cdot e^{-\tau} \quad (6)$$

This is Eq (39) of Reference 1. It should be remembered that $Z_0 = 500$ km and $150 \leq Z < 500$ km when this equation is applied. Here

$$\tau \equiv U = \int_{Z_0}^Z f(Z) dZ$$

The integral in Eq (6) is evaluated numerically by Simpson's 1/3 Rule. The method used is identical to that described in Section 2.3.1. Note that if the calculation does not converge to the preselected limit, $\epsilon = 0.0001$, the last estimate U_{10} is accepted as the value of the integral and an error message is printed.

2.4.2 Function FX(Z)

The Function FX(Z) is given by

$$FX = \frac{\phi}{D(H)} \left(\frac{T(Z)}{T(Z_0)} \right) e^{\tau}$$

from Eq(6). As before the molecular diffusion coefficient $D(H)$ depends upon the total number density. In Function F(Z) the diffusion coefficient was approximated by a fourth order polynomial, here the altitude range for the integral is too large. Consequently, the total number density N was approximated by

$$\ln N = a_0^i + a_1^i Z + a_2^i Z^2 + a_3^i Z^3 + a_4^i Z^4$$

where the superscript is added because the approximation is divided into four regions

$$i = \begin{cases} 1 & 150 < Z \leq 240 \\ 2 & 240 < Z \leq 340 \\ 3 & 340 < Z \leq 440 \\ 4 & 440 < Z \leq 500 \end{cases}$$

The diffusion coefficient was then computed from this total number density by

$$D(H) = \frac{a}{N} \left[\frac{T}{T_0} \right]^b$$

where a , b , and T_0 are constants defined in Reference 1.

III. PROGRAM USE

The US 76 computer program was designed in a modular fashion, meaning that certain sections of the program can be easily adapted for use without using the entire subroutine package. This is accomplished by making various sections independent of the other sections of the program and by keeping the subroutine interfaces or linkages simple. In this section the input and output of the program are described. The common blocks are also described so that similar names or parameters can be avoided in the user's program or easily changed in the US 76 subroutine package. The interfaces between routines are discussed along with possible segmenting of the subroutine package.

3.1 INPUT/OUTPUT

Subroutine US 76 has six arguments

SUBROUTINE US76(Z, ID, DEN, PRES, TEMP, A)

The only inputs are the altitude Z given in kilometers and an indicator ID which is a constant equal to or greater than zero. The outputs are density DEN given in $\text{kg} \cdot \text{m}^{-3}$, the pressure PRES given in millibars and the temperature TEMP given in degrees Kelvin. Additional output is stored in the vector A which is dimensioned A(7) and needs to be so dimensioned in the calling program. Below 86 km the vector A may contain dynamic and kinematic viscosity, thermal conductivity, mean free path collision frequency, particle velocity and speed of sound. All of these are given in metric units corresponding to those found in Reference 1. Above 86 km the vector A contains the number densities of the six constituents and the total number density given in per cubic meter.

The input and output are summarized in Figure III-1. The output allows the user to reproduce most of the data found in the tables of Reference 1. However, many parameters are not

made available to the user without suitable calculations or conversions made in the calling program. At no altitude is geopotential height or any parameter as a function of geopotential height given. English units are not used in this subroutine package. Ratios of parameters which are found in the tables of Reference 1 are not available from these routines. In addition, the acceleration of gravity, while calculated in the routines, is not available as output nor is the mean molecular weight nor is the total number density below 86 km. The pressure scale height is not computed. With these exceptions the tables of Reference 1 can be reproduced to three significant figures.

3.1.1 Error Messages

There are two error messages which the user could encounter but are unlikely to occur without some modification of the subroutine package or the code itself. In general, the only error the user can make, if he calls the US 76 subroutine with the proper list, is to specify an altitude outside the range. This could occur if a negative altitude or an altitude greater than 1000 km was requested. This latter could easily occur if the calling program is working in English units and no conversion to metric is made before calling US 76. This error will not result in an error message but will result in the output for all parameters being zero.

It should be noted that none of the main subroutines LDEN, MDEN or NDEN checks altitude, this is a user responsibility if the calling routine US 76 is not used. However, in INTEG which is called by MDEN if the altitude is less than 86 km or greater than 120 km an error message will be written and the integral will be evaluated as zero. The calculation will not be terminated.

The second error message can be generated either in INTEG or in NHYD if the numerical integration fails to converge in the specified number of steps. In this case the last computed value of the integral is taken and the calculation allowed to continue. This contingency has not occurred under normal use and would probably only occur should the user modify the convergence criteria ϵ

$$\left| \frac{U_k - U_{k-1}}{U_k} \right| < \epsilon$$

or modify the number of steps, k , taken before discontinuing the numerical integration.

3.2 COMMON BLOCKS

The only common blocks occur in routines NDEN, INTEG and FX(Z) which are called for altitudes above 120 km. Two common blocks are defined in NDEN

```
COMMON /BLK2/ AH, XN11, T11, Z11, XMH
COMMON /BLK3/ TINF, RAD, XL.
```

These blocks are used to transfer data to NHYD and FX(Z) and could be replaced with the appropriate DATA statement.

3.3 PROGRAM MODIFICATION

3.3.1 Subroutine Interfaces

The interfaces between the subroutine US 76 and the main subroutines are all similar. The call to LDEN requires only four parameters

```
CALL LDEN(Z,DEN,TEMP,PRES).
```

The altitude Z which is input from the calling routine to LDEN and density DEN , temperature $TEMP$, and pressure $PRES$ which are output from LDEN to the calling program. The calling sequence for MDEN and NDEN are identical and are the same as LDEN except for two additional terms

```
CALL MDEN(Z,DEN,TEMP,PRES,A(1),A(7) )
CALL NDEN(Z,DEN,TEMP,PRES,A(1),A(7) )
```

The first of these terms, which as shown here as A(1), is a variable, dimensioned at least 6 locations, and is used to output number densities of the constituents. The other term A(7) requires only one location and is used to output total number density.

The routines AUX1 and AUX2 are independent of LDEN but require output from LDEN to complete their calculations. Subroutine AUX1 requires

```
CALL AUX1(Z,TEMP,PRES,A(6),A(4),A(5),A(7) )
```

altitude, temperature and pressure as input. The output consists of particle velocity A(6), mean free path A(4), collision frequency A(5), and speed of sound A(7). Subroutine AUX2 requires altitude, temperature and

```
CALL AUX2(Z,TEMP,DEN,A(1),A(2),A(3) )
```

density as input. The output consists of dynamic A(1) and kinematic A(2) viscosity and thermal conductivity A(3).

The linkage between MDEN and INTEG consists of only three parameters. The input to INTEG is the

```
CALL INTEG(N,Z,C)
```

constituent index N and the altitude Z. The output is the value of the numerical integration. The interface between INTEG and F(Z) is a function

```
FUNCTION F(Z,N)
```

link requiring as input the altitude and constituent index.

The link between NDEN and NHYD consists of three input parameters and one dimensioned variable to provide output. The inputs are the altitude Z,

```
CALL NHYD(Z,T,T10,XN)
```

the temperature T and a constant temperature at 120 km T10. The output requires a dimensioned variable XN(6) but only the last position is modified. The interface between NHYD and FX(Z) is a functional linkage requiring only the altitude Z.

FUNCTION FX(Z)

as input.

3.3.2 Modification of Program

The simplest modification of the subroutine package would be to remove the calling routine as shown in Figure III-2. This allows the user to select only that portion of the code relevant to his problem.

If the user is interested only in the 0 to 86 km altitude range then AUX1 or AUX2 could be deleted. Alternately if the parameters computed by AUX1 and or AUX2 were required for known input then they could be used independently.

Another modification would be the construction of a new calling routine to produce the thermosphere model shown on Figure III-3. This would be necessary if the entire altitude range 86 to above 120 km was required.

Finally, very simple modifications of the code of INTEG would permit the use of this routine as a general Simpson's 1/3 Rule for which the user supplies the function F(Z).

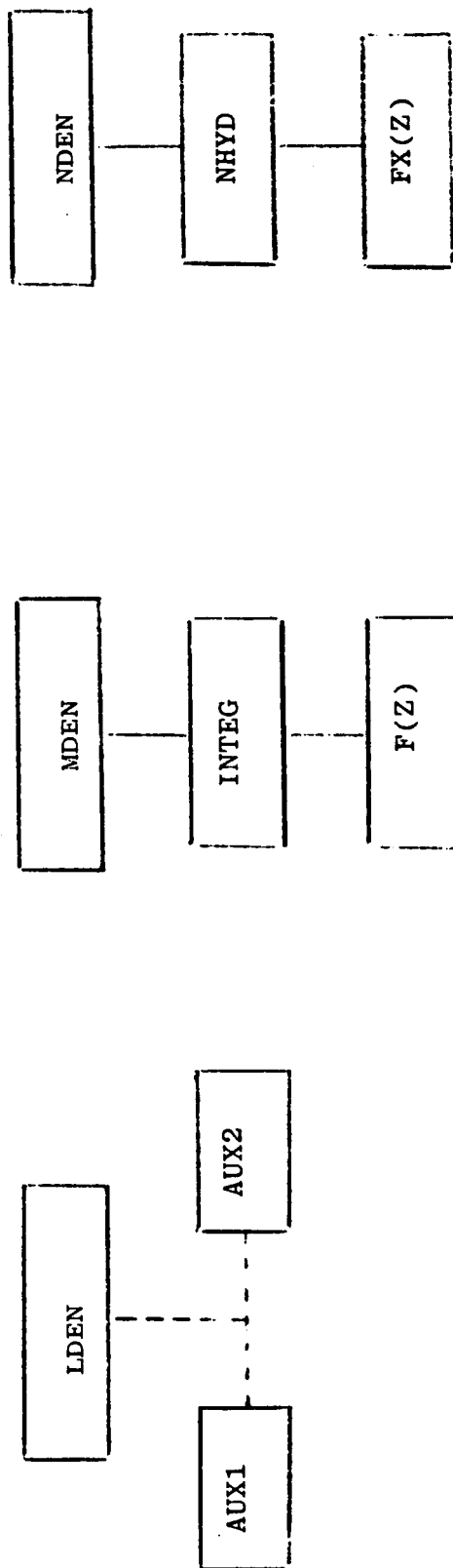


Figure III-2. Modification of US 76 by Separation of Subroutine Subroutines

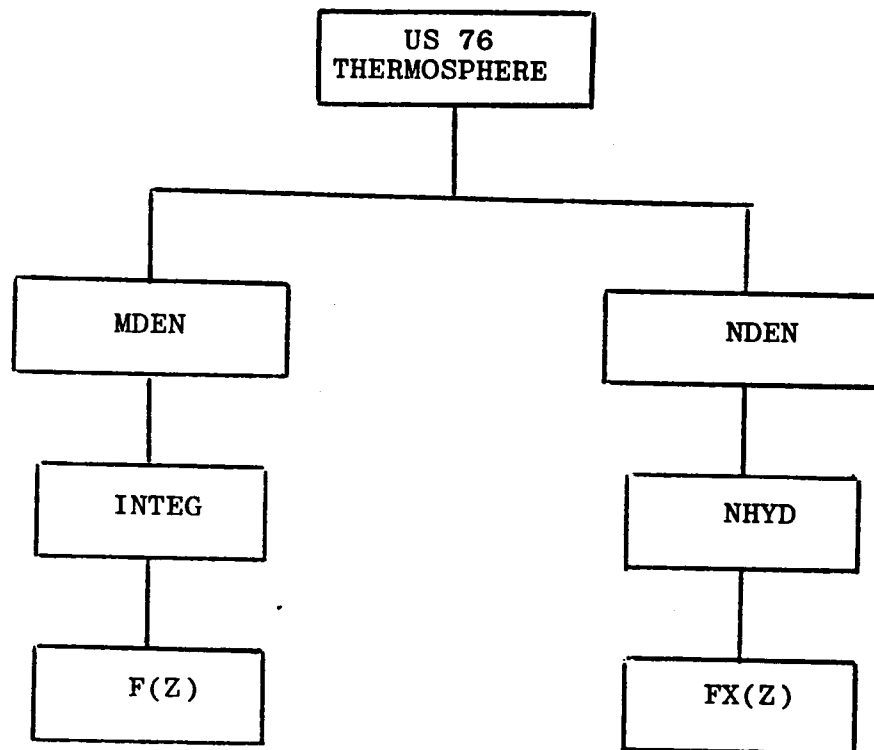


Figure III-3. Modification of US 76 for Thermosphere Model

IV. MODEL REVIEW

The U.S. Standard Atmosphere, 1976, is a static model representative of conditions in mid-latitudes during moderate solar activity. As such it presents a single temperature profile from the surface to 1000 km as well as single profiles of density, pressure, mean molecular weight and all other parameters. The US 76 is useful for obtaining representative values of atmospheric parameters when deviations from these values are not important to the user. However, "because of variability of atmospheric conditions with spacial location and solar conditions, invariant models of the earth's atmosphere (90 to 2500 km) are not useful for most engineering applications" (Ref. 2). Moreover, where engineering applications tend to require a global view as opposed to a mid-latitude view, a similar statement must hold for the atmosphere from the surface to 90 km.

The variability of the atmospheric structure can easily be seen from spacial and temporal distributions of the temperature. Figure IV-1 illustrates the distribution as observed, in the mean, between the surface and 80 km (Ref. 3). Comparison of this figure with Figure II-1 reveals the similarity of the US 76 temperature profile with that for the summer months at about 45° latitude: $\sim 290^{\circ}\text{K}$ at the surface, 220° at 20km, 280°K at 50 km and 190°K above 70 km. A somewhat different profile would be indicated even for the winter months at mid-latitudes. Figures IV-2 and 3 give a more detailed description of the region between 40 km and 90 km. From these three figures a general agreement about the temperature distribution can be seen even if the specifics differ. Finally, Figure IV-4 illustrates the observed diurnal and latitudinal variability of the thermosphere temperature by means of the global distribution of exospheric temperature.

Since the publication of the US 62 there has been a trend toward incorporating the observed variability of the atmosphere in Reference Atmospheres, particularly the variability

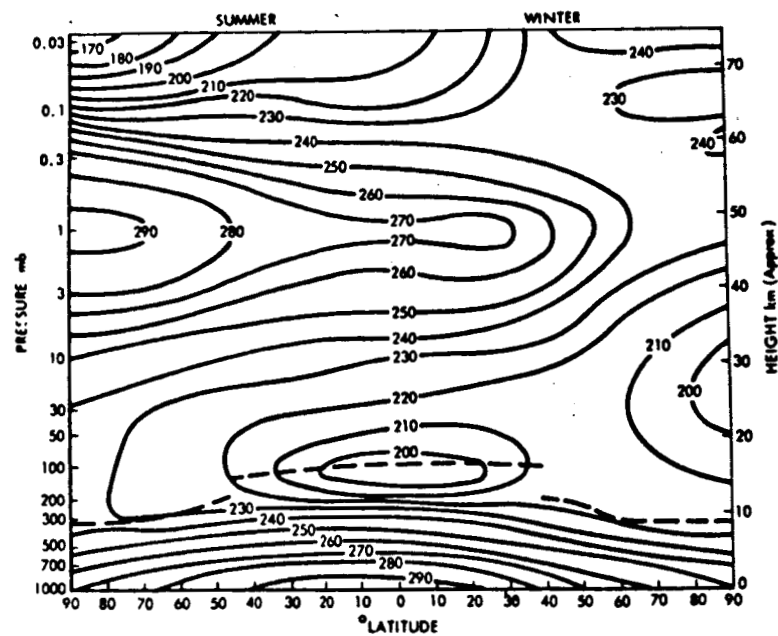


Figure IV-1. Latitudinal and Seasonal Variation of Temperature with Altitude at Solstice (Ref. 3)

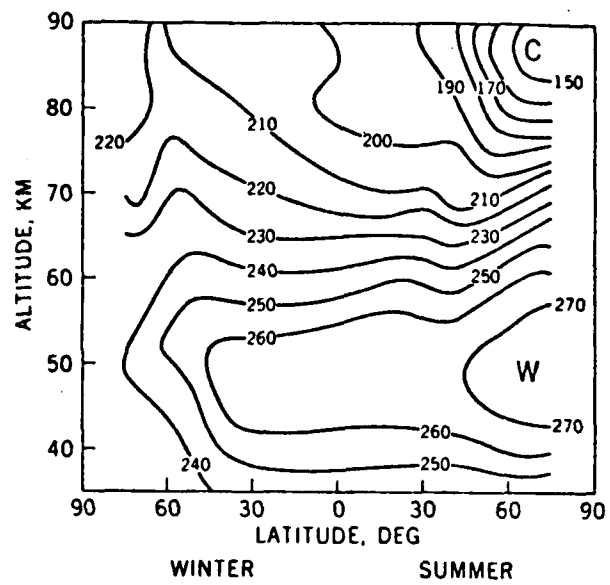


Figure IV-2. Latitudinal and Seasonal Variation of Temperature with Altitude at Solstice. (Ref. 4)

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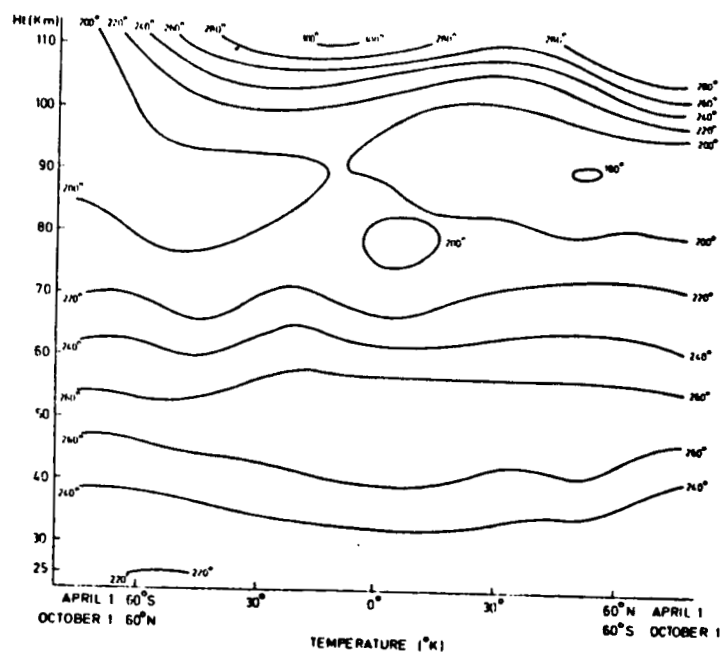
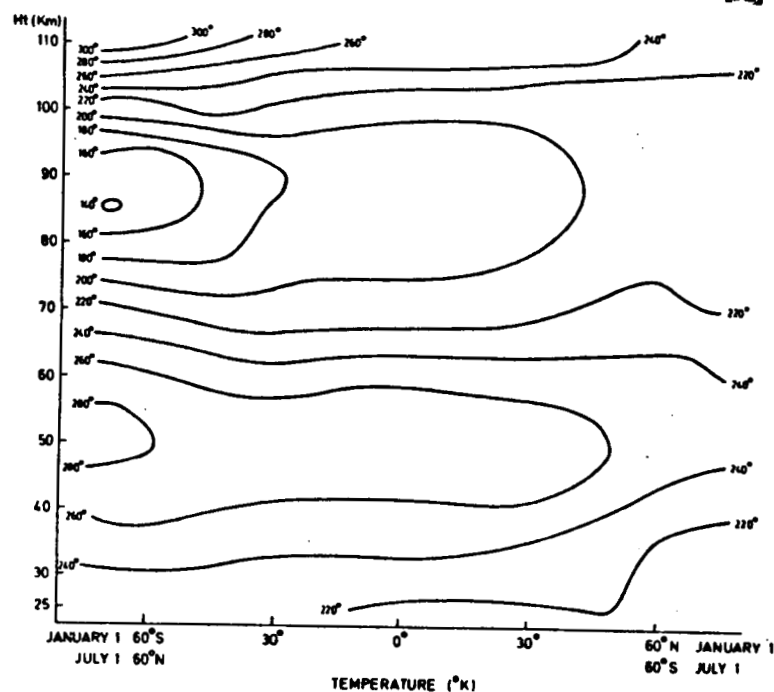


Figure IV-3. Latitudinal and Seasonal Variation of Temperature
with Altitude (Ref. 5)

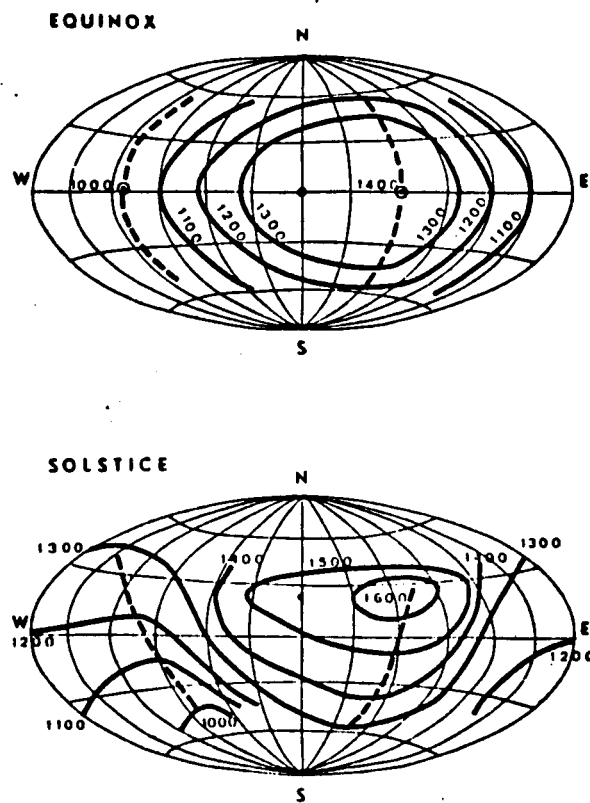


Figure IV-4. Diurnal Variation of Exospheric Temperature as Observed by Thomson Scatter (Ref. 6)

above 90 km. Most notable of these Reference Atmospheres were the COSPAR International Reference Atmosphere of 1965 (CIRA 1965) and the U. S. Standard Atmosphere Supplements, 1966 (US 66). The US 66 included latitudinal and seasonal variability, by means of tables, of the atmosphere below 120 km and an analytic representation of the atmosphere above 120 km accounting for variations due to variable solar activity. More recently, a summarization of stratosphere and mesosphere data by Groves (Ref. 5), part of which is shown in Figure IV-3, and a revised Thermosphere model by Jacchia J71 (Ref. 7) have been combined to form the basis of the CIRA 1972. Figure IV-5 illustrates the distribution of exospheric temperature according to J71. The NASA/MSFC Global Reference Atmosphere (Ref. 8) also uses Grove's model of the middle atmosphere and a Jacchia Thermosphere Model J70 (Ref. 9). However, the Global Reference Atmosphere also includes the Four Dimensional World-Wide Atmosphere Model (Ref. 10) to provide the atmospheric variability from the surface to 25 km.

The US 76 viewed from a perspective including recent trends in the representation of atmospheric variability appears to be somewhat of an anachronism and in need of a new "Supplement". The thermospheric temperature structure of US 76 is very similar to that found in US 66 and would lend itself to simple modification to incorporate solar variability. Figure IV-6 suggests how that program modification could be made by incorporating a new subroutine to calculate the exospheric temperature. However, this simple approach is also anachronistic in that it ignores the trend in thermosphere model development. In fact, a more likely approach would be the far more complicated integration of Jacchia's latest thermosphere model J77 (Ref. 11) into any new Reference Atmosphere, the thermosphere temperature distribution for this model is shown in Figure IV-7.

Thus, it would appear that the US 76 while being the most recent of the Reference Atmospheres, will find limited use

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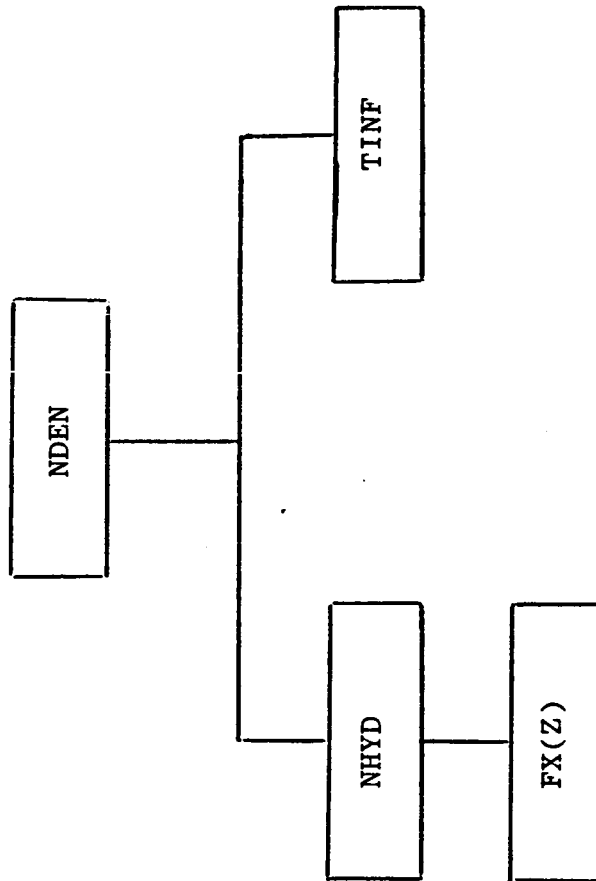
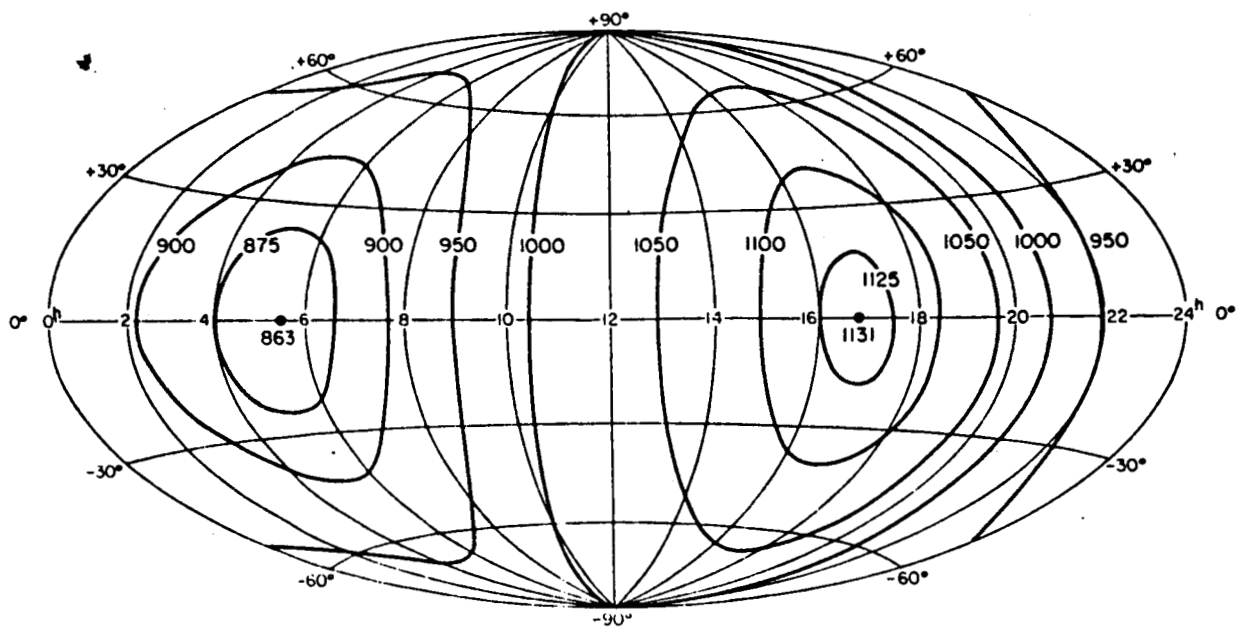
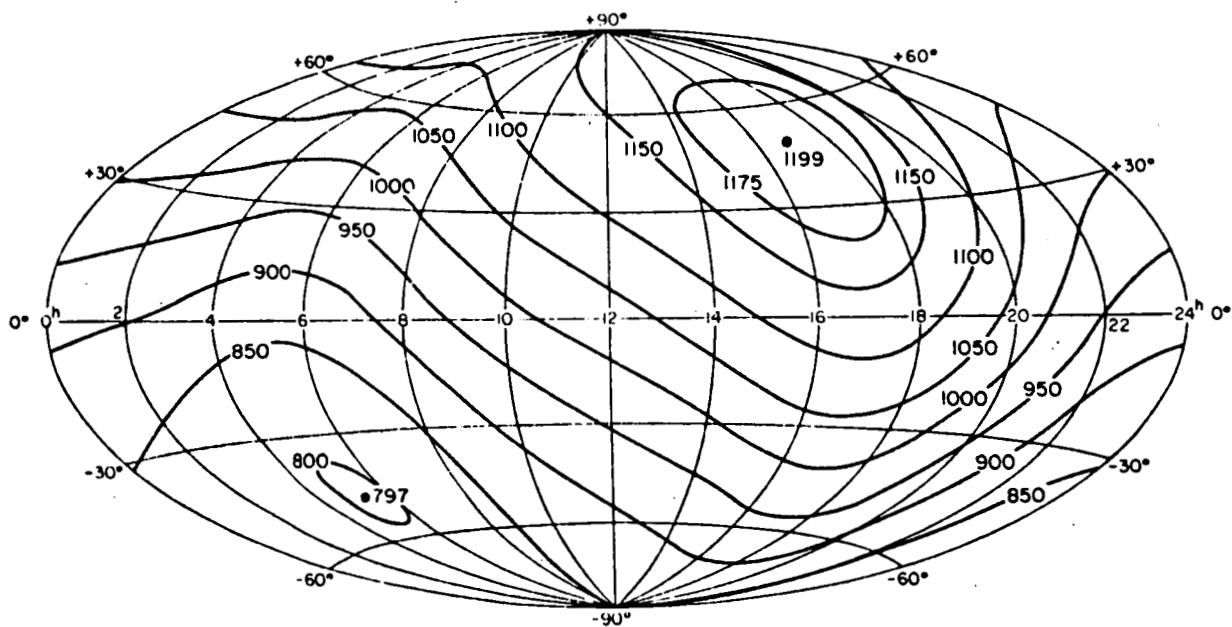


Figure IV-6. A "Jacchia 1976" Thermosphere Model



a) Equinoxes.



b) June solstice.

Figure IV-7. Diurnal Variation of Exosphere Temperature from J77 (Ref. 10)

in the engineering community. However, because it is the U. S. Standard Atmosphere it will certainly be the standard against which all other Reference Atmospheres will be measured.

V. SUMMARY

A computer version of the recently published U. S. Standard Atmosphere, 1976, has been developed. The computer program has been developed in modular form for easy incorporation into the user's program and for easy modification for specialized uses. Because of the lack of atmospheric variability the US 76 will find limited use in aerospace research. However, it will become the standard against which all other atmospheric models will be measured.

VI. REFERENCES

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APPENDIX

PROGRAM LISTING

```

(POR,IS MAIN,MAIN
C
C   PROGRAM US76 CHECK
C
C   DIMENSION A(7)
C   Z = 0.
C   ID = 3
C   WRITE(6,9002)
9002 FORMAT(?'?)
C   DO 100 J=1,200
C   Z = Z + 5.
C   CALL US76(Z,ID,DEN,PRES,TEMP,A)
C   WRITE(6,9001) Z,DEN,PRES,TEMP,(A(I),I=1,7)
9001 FORMAT(2X,F6.1,3X,E12.4,3X,F7.2/9X,7(3X,E12.4) )
C   100 CONTINUE
C   STOP
C   END
(POR,IS US76,US76
C   SUBROUTINE US76(Z,ID,DEN,PRES,TEMP,A)
C
C   US76 IS A CALLING SUBROUTINE FOR THE U.S. STANDARD ATMOSPHERE, 1976
C
C
C   INPUT      Z      ALTITUDE(KM)
C              ID      INDICATOR
C
C   OUTPUT     DEN     DENSITY (KG/M**3)
C              PRES    PRESSURE (MB)
C              TEMP    TEMPERATURE (DEG K)
C              A(7)    ADDITIONAL VARIABLES DEPENDENT ON ID
C
C   INDICATOR INPUT
C
C   Z,LT,86KM   ID = 0   NO ADDITIONAL OUTPUT
C                ID = 1   VISCOSITY AND THERMAL CONDUCTIVITY
C                ID = 2   MEAN FREE PATH, COLLISION FREQUENCY, MEAN
C                        PARTICLE VELOCITY, AND SPEED OF SOUND
C                ID = 3   BOTH THE ABOVE
C
C   Z,GE,86KM   ID = 0   NO ADDITIONAL OUTPUT
C                ID = 1-3  CONSTITUENT AND TOTAL NUMBER DENSITIES
C
C   INDICATOR OUTPUT
C   Z,LT,86KM   A(1)     DYNAMIC VISCOSITY (N*SEC/M**2)
C                A(2)     KINEMATIC VISCOSITY (M**2/SEC)
C                A(3)     THERMAL CONDUCTIVITY (J/M*SEC*DEG K)
C                A(4)     MEAN FREE PATH (M)
C                A(5)     COLLISION FREQUENCY (1/SEC)
C                A(6)     PARTICLE VELOCITY (M/SEC)
C                A(7)     SPEED OF SOUND
C
C   Z,GE,86KM   A(1)     N2 NUMBER DENSITY
C                A(2)     O1 NUMBER DENSITY
C                A(3)     O2 NUMBER DENSITY
C                A(4)     AR NUMBER DENSITY
C                A(5)     HE NUMBER DENSITY
C                A(6)     H1 NUMBER DENSITY
C                A(7)     TOTAL NUMBER DENSITY
C

```



```

      DIMENSION A(7)
C
      DEN = 0.
      PRES = 0.
      TEMP = 0.
      DO 10 I=1,7
10  A(I) = 0.
C
      IF( (Z,LT,0.),OR,(Z,GT,1000.) )      RETURN
C
      IF( (Z,GE,0.),AND,(Z,LT,86.) )
      * CALL LDEN(Z,DEN,TEMP,PRES)
      IF( (Z,GE,86.),AND,(Z,LT,120.) )
      * CALL MDEN(Z,DEN,TEMP,PRES,A(1),A(7) )
      IF( (Z,GE,120.),AND,(Z,LE,1000.) )
      * CALL NDEN(Z,DEN,TEMP,PRES,A(1),A(7) )
C
      IF( (ID,EQ,0),OR,(ID,GT,3) )      RETURN
      IF(Z,GE,86.)      RETURN
      IF( (ID,EQ,1),OR,(ID,EQ,3) )
      * CALL AUX2(Z,TEMP,DEN,A(1),A(2),A(3) )
      IF( (ID,EQ,2),OR,(ID,EQ,3) )
      * CALL AUX1(Z,TEMP,PRES,A(6),A(4),A(5),A(7) )
      RETURN
      END
(POR,IS LDEN,LDEN
      SUBROUTINE LDEN(Z,DEN,T,PRES)
      DATA AF/34,16319474/ RAD/6356,766/
C
C  COMPUTE GEOPOTENTIAL HEIGHT H
C
      H = RAD*Z/(RAD + Z)
C
C  COMPUTE TEMPERATURE
C
      IF( H,LT,11. )
      * T = 288.15 - 6.5*H
      IF( (H,GE,11.),AND,(H,LT,20.) )
      * T = 216.65
      IF( (H,GE,20.),AND,(H,LT,32.) )
      * T = 216.65 + (H - 20.)
      IF( (H,GE,32.),AND,(H,LT,47.) )
      * T = 228.65 + 2.8*(H - 32.)
      IF( (H,GE,47.),AND,(H,LT,51.) )
      * T = 270.65
      IF( (H,GE,51.),AND,(H,LT,71.) )
      * T = 270.65 + 2.8*(H - 51.)
      IF( (H,GE,71.),AND,(H,LT,86.) )
      * T = 214.65 + 2.0*(H - 71.)

```

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C
C
C

COMPUTE DENSITY

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```

      IF( H,LT,11. )
      *   DEN = 1.225*(288.15/T)**(1. - AF/6.5)
      IF( (H,GE,11.),AND.(H,LT,20. ) )
      *   DEN = 3.6392E-01*EXP(-AF*(H - 11.)/216.65)
      IF( (H,GE,20.),AND.(H,LT,32. ) )
      *   DEN = 8.8035E-02*(216.65/T)**(1. + AF)
      IF( (H,GE,32.),AND.(H,LT,47. ) )
      *   DEN = 1.3225E-02*(228.65/T)**(1. + AF/2.8)
      IF( (H,GE,47.),AND.(H,LT,51. ) )
      *   DEN = 1.4275E-03*EXP(-AF*(H - 47.)/270.65)
      IF( (H,GE,51.),AND.(H,LT,71. ) )
      *   DEN = 8.616E-04*(270.65/T)**(1. - AF/2.8)
      IF( (H,GE,71.),AND.(H,LT,86. ) )
      *   DEN = 6.4211E-05*(214.65/T)**(1. - AF/2. )

```

C
C
C

COMPUTE PRESSURE

```

      PRES = 2.87053072*DEN*T
      RETURN
      END

```

IFOR, IS AUX1, AUX1

SUBROUTINE AUX1(Z,T,PRES,V,XL,C,CS)

C
C
C
C
C

AUX1 COMPUTES MEAN AIR PARTICLE SPEED V, MEAN FREE PATH XL
MEAN COLLISION FREQUENCY C, AND SOUND SPEED CS BELOW 86KM
GIVEN ALTITUDE Z(KM), TEMPERATURE T(K), AND PRESSURE PRES(MB).

```

      V = 0.
      XL = 0.
      C = 0.
      CS = 0.
      IF( Z,GT,86. ) RETURN

```

C
C
C

COMPUTE MEAN AIR PARTICLE SPEED V(M/SEC)

```

      V = 27.03654*SQRT( T )

```

C
C
C

COMPUTE MEAN FREE PATH XL(M)

```

      XL = 2.332508E-07*T/PRES

```

C
C
C

COMPUTE MEAN COLLISION FREQUENCY C(1/SEC)

```

      C = V/XL

```

C
C
C

COMPUTE SOUND SPEED CS(M/SEC)

```

      CS = 20.0468*SQRT( T )

```

C
C
C

```

      RETURN
      END

```

IFCR, IS AUX2, AUX2

SUBROUTINE AUX2(Z,T,DEN,VISDYN,VISKIN,TCOND)

C
C AUX2 COMPUTES DYNAMIC VISCOSITY VISDYN, KINEMATIC VISCOSITY VISKIN,
C AND THE COEFFICIENT OF THERMAL CONDUCTIVITY TCOND BELOW 86KM
C GIVEN ALTITUDE Z(KM), TEMPERATURE T(K) AND DENSITY(KG/M**3),
C

VISDYN = 0.

VISKIN = 0.

TCOND = 0.

IF(Z.GT.86.) RETURN

C
C COMPUTE DYNAMIC VISCOSITY (N*SEC/M**2)

VISDYN = 1.458E-06*(T**1.5)/(T + 110.4)

C
C COMPUTE KINEMATIC VISCOSITY (M**2/SEC)

VISKIN = VISDYN/DEN

C
C COMPUTE COEFFICIENT OF THERMAL CONDUCTIVITY (J/M*SEC*K)

TCOND = (2.64752E-03*(T**1.5))/(T + 245.4*10**(-12./T))

C
RETURN

END

(FOR,IS MDEN,MDEN

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SUBROUTINE MDEN(Z,DEN,T,PRES,XN,XNTOT)

DIMENSION Q(2,5),W(2,5),U(2,5),XMT(5)

DIMENSION XN(6),XN0(5)

DATA XN0/1,130E+20,8,6E+16,3,031E+19,1,351E+18,7,582E+14/

DATA Q/0.,0.,-5.809644E-04,-3.416248E-03,1.366212E-04,

* 0.,9.434079E-05,0.,-2.457369E-04,0./ W/0.,0.,2.706240E-05,

* 5.008765E-04,8.333333E-05,0.,8.333333E-05,0.,6.666667E-04,0./

* U/0.,0.,56.90311,97.,86.,0.,86.,0.,86.,0./ XM/28.0134,15.9994,

* 31.9988,39.948,4.0026/

DATA GAS/8,31432/ BOLTZ/1.380622E-23/

NAMLIST/DCHK/N,Z,C,FACT1,FACT2,FACT3,FACT

XN(6) = 0.

XNTOT = 0.

XMM = 0.

C

C

COMPUTE TEMPERATURE

C

T = 186.8673

IF((Z,GE.91.),AND.(Z,LT.110.))

1T = 263.1905 - 76.3232*(1 - ((Z-91.)/19.9429)**2)**.5

IF(Z,GE.110.) T=240. + 12*(Z-110.)

C

C

COMPUTE NUMBER DENSITIES

C

DO 100 I=1,5

N = I

CALL INTEG(N,Z,C)

FACT1 = 186.8673/T

FACT = 1.

IF(I,EQ.1) GO TO 100

FACT2 = Q(1,N)/(3.+W(1,N))*(EXP(-W(1,N)*(86.-U(1,N))**3) - EXP(-

W(1,N)(Z-U(1,N))**3))

FACT3 = 0.0

IF((Z,LE.97.),AND.(N,EQ.2)) FACT3 = Q(2,N)/(3.+W(2,N))*(EXP(-

W(2,N)(U(2,N)-86.)**3) - EXP(-W(2,N)*(U(2,N)-Z)**3))

IF((Z,GT.97.),AND.(N,EQ.2))

* FACT3 = -1.1062525

FACT = EXP(-(FACT2 + FACT3))

100 XN(I) = XN0(I)*FACT*FACT1*EXP(-C)

C

C

COMPUTE DENSITY

C

DEN = 0.

DO 200 I=1,5

XNTOT = XNTOT + XN(I)

200 XMM = XMM + XM(I)*XN(I)

XMM = XMM/XNTOT

PRES = XNTOT*BOLTZ*T

DEN = (PRES*XMM)/(GAS*T)

PRES = PRES*1.E-02

DEN = DEN*1.E-03

C

RETURN

END

```

IFOR,IS INTEG,INTEG
  SUBROUTINE INTEG(N,Z,U2)
  NAMELIST /ICLK/ N,Z,J,U1,U2
  U2 = 0.
  IF( (Z,LT,86).OR.(Z,GT,120.) ) GO TO 300
  J = 1
  H = (7-86.)/2.
  XK = H/3.
  A0 = F(Z,N) + F(86.,N)
  X = 86. + H
  A1 = F(X,N)
  B1 = A0 + 4*A1
  U1 = XK*B1
  A0 = A1
C
  10 JL = 2+J
  A1 = 0.
C
  DO 100 I=1,JL
  K = (I-1)*2 + 1
  X = 86. + K*H/JL
  100 A1 = A1 + F(X,N)
C
  XK = XK/2.
  B2 = B1 - 2*A0 + 4*A1
  U2 = XK*B2
  TEST = ABS( (U2 - U1)/U2 )+100.
  IF(TEST,LT,0.010) RETURN
  IF(J,GT,10) GO TO 200
  J = J + 1
  B1 = B2
  A0 = A1
  U1 = U2
  GO TO 10
C
  200 WRITE(6,9001) U1,U2
  RETURN
  300 WRITE(6,9002) Z
  RETURN
9001 FORMAT(71INTEGRAL FAILED TO CONVERGE7/2E12,4)
9002 FORMAT(71ALTITUDE OUTSIDE RANGE7/E12,4)
  END

```

```

IFOR,IS F,F
  FUNCTION F(Z,N)
  DIMENSION C(5,5),B(5),A(5),XM(5)
  DATA RSTAR/8,31432/ B/-7,347377E+02,2.656098E+01,
  * -3,424545E-01,1.9413285E-03,-4.097465E-06/
  * C/0.,0.,0.,0.,0.,-2.573835E+02,1.056895E+01,-1.495593E-01,
  * 1.000696E-03,-2.4956E-06,-2.577458E+02,1.005896E+01,-1.495594E-01,
  * 1.000696E-03,-2.4956E-06,-2.701692E+02,1.056359E+01,-1.574121E-01,
  * 1.054529E-03,-2.63274E-06,-2.359003E+02,9.253264,
  * -1.379937E-01,9.279475E-04,-2.327176E-06/
  DATA XM/28,0134,15.9994,31.9988,39.948,4.0026/ A/0.,0.,0.,0.,-4/

```

```

C
C COMPUTE TEMPERATURE
C
  T = 186.8673
  IF((Z,GT,91.),AND,(Z,LT,110.))
  1 T = 263.1905 - 76.3232*((1 - ((Z-91.)/19.9429)**2)**.5
  IF(Z,GE,110.) T = 240. + 12*(Z-110.)
C
C COMPUTE GRAVITY
C
  G = 9.80665*(6356.766/(6356.766 + Z) )**2
  FACT1 = G/(RSTAR*T)
C
C COMPUTE MEAN MOLECULAR WEIGHT
C
  XMM = 28.9644
  IF(Z,LE,100.) GO TO 30
  XMM = 28.0134
  IF(N,GT,3)
  * XMM = B(1) + Z*(B(2) + Z*(B(3) + Z*(B(4) + Z*B(5) )))
30 CONTINUE
  FACT2 = 1.
  FACT3 = XMM
  FACT4 = 0.
  IF(N,EQ,1) GO TO 50
C
C COMPUTE TEMPERATURE GRADIENT
C
  DT = 0.0
  IF((Z,GT,91.),AND,(Z,LT,110.))
  * DT = -3.8271*((Z-91.)/(-19.9429))/((1-((Z-91.)/19.9429)**2)**.5
  IF(Z,GE,110.) DT = 12.0
C
C COMPUTE EDDY DIFFUSION COEFFICIENT
C
  XK = 0.
  IF(Z,LE,95.) XK = 120.
  IF( (Z,GT,95.),AND,(Z,LT,115.) )
  * XK = 120.*EXP( 1 - (400./((400. - (Z - 95.))**2)) )
C
C COMPUTE MOLECULAR DIFFUSION COEFFICIENT
C
  D = EXP( C(1,N) + Z*(C(2,N) + Z*(C(3,N) + Z*(C(4,N) + Z*C(5,N)))) )
20 CONTINUE
C
C COMPUTE F(Z) FROM EQUATION 36
C
  FACT2 = 1./(D + XK)
  FACT3 = D*XM(N) + XMM*XK
  FACT4 = (A(N)*RSTAR/G)*DT*D
50 F = FACT1*FACT2*(FACT3 + FACT4)
  RETURN
  END

```

```

(POR,IS NDEN,NDEN
  SUBROUTINE NDEN(Z,T,DENS,PRES,XN,XNTOT)
C
C  US 76 STANDARD ATMOSPHERE FOR ALTITUDES ABOVE 120KM
C
C  NDEN COMPUTES NUMBER DENSITIES OF ALL NEUTRAL ATMOSPHERIC
C  CONSTITUENTS EXCEPT HYDROGEN ABOVE 120KM GIVEN ALTITUDE Z AND TEMPERATURE
C
C
C  DIMENSION XN(6)
C  COMMON /BLK2/ AH, XN11, T11, Z11, XMH
C  COMMON /BLK3/ TINF, RAD, XL
C
C
C  DATA A/0,0,0,0,-0.4/ AH/-0.25/ T10/360./ T11/999.2356/ TINF/1000./
C  *Z10/120./ Z11/500./ GAS/H,31432/ BOLTZ/1.3806622E-23/ XL/0.01875/
C  *B/0.060596/ G/0.0011362/ RAD/6356.766/
C
C  DATA Q/0,-5.809644E-04, 1.366212E-04, 9.434079E-05, -2.457369E-04/
C  *W/0, 2.706242E-05, 8.333333E-05, 8.333333E-05, 6.666667E-04/
C  *U/0, 56.90311, 86., 86., 86./
C
C  DATA XN10/3.726E+17, 9.275E+16, 4.395E+16, 1.366E+15, 3.888E+13/
C  *XM/28.0134, 15.9994, 31.9988, 39.940, 4.0026, 1.00797/ XMH/1.00797
C  */XN11/8.0E+10/
C
C  XN(6) = 0.
C
C  COMPUTE GEOPOTENTIAL ALTITUDE E      EQ(OI) + 2
C
C  
$$E = (Z - Z10) * (RAD + Z10) / (RAD + Z)$$

C
C  COMPUTE TEMPERATURE
C
C  
$$T = TINF - (TINF - T10) * EXP(-XL * E)$$

C
C  COMPUTE NUMBER DENSITIES OF ALL CONSTITUENTS EXCEPT HYDROGEN
C
C
C  DO 50 I=1,5
C    TFACT = (T10/T)**(1. + A(I) + B*XN(I))
C    EFACT = EXP(-G*XN(I)*E)
C    FACT = 1.0
C    IF(I,EQ,1) GO TO 10
C    FACT1 = EXP(-W(I)*(Z - U(I))**3)
C    FACT2 = EXP(-W(I)*(Z10 - U(I))**3)
C    FACT = EXP( Q(I)*(FACT1 - FACT2)/(3.*W(I)) )
C  10 XN(I) = XN10(I)*TFACT*EFACT*FACT
C  50 CONTINUE
C
C  COMPUTE TOTAL NUMBER DENSITY
C
C  XNTOT = 0.
C  DO 200 I=1,5
C  200 XNTOT = XNTOT + XN(I)
C

```

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C
C
C COMPUTE HYDROGEN NUMBER DENSITY IF Z GT 150
C
C   IF(Z,GE,150.)    CALL NHYD(Z,T,T10,XN)
C
C COMPUTE TOTAL NUMBER DENSITY, PRESSURE, MEAN MOLECULAR WEIGHT, AND DENSITY
C
C   PRES = 0
C   XNTOT = XNTOT + XN(6)
C   XM0 = 0.
C
C   DO 100 I=1,6
C   XM0 = XM0 + XN(I)*XM(I)
100 PRES = PRES + XN(I)*BOLTZ*T
C
C   XM0 = XM0/XNTOT
C   DENS = (PRES*XM0)/(GAS*T)
C   PRES = PRES*1.E-02
C   DENS = DENS*1.E-03
C
C   RETURN
C   END

```

```

[FOR, IS NHYD, NHYD
  SUBROUTINE NHYD(Z,T,T10,XN)
C
C NHYD COMPUTES HYDROGEN NUMBER DENSITY ABOVE 150KM
C
C   DIMENSION XN(6)
C   COMMON /BLK2/ AH, XN11, T11, Z11, XMH
C   COMMON /BLK3/ TINF, RAD, XL
C
C   DATA B/0.0540664/ G/0.0010137/
C
C   XN(6) = 0.
C   IF(Z,LT,150.) RETURN
C
C   E = (Z - Z11)*(RAD + Z11)/(RAD + Z)
C
C   TFACT = (T11/T)**(1. + AH + B*XMH)
C   EFACT = EXP(-G*XMH*E)
C   XN(6) = XN11*TFACT*EFACT
C   IF(Z,GE,500.) RETURN

```



```

C
C COMPUTE HYDROGEN INTEGRAL EQ(39) USING SIMPSON RULE
C
  U2 = 0.
  J = 1
  H = (Z - 500.)/2.
  XK = H/3.
  A0 = FX(Z) + FX(500.)
  X = 500. + H
  A1 = FX(X)
  B1 = A0 + 4.*A1
  U1 = XK*B1
  A0 = A1
C
10 JL = 2.**J
  A1 = 0.
C
  DO 100 I=1,JL
    K = (I - 1)*2 + 1
    X = 500. + K*H/JL
100 A1 = A1 + FX(X)
C
  XK = XK/2.
  B2 = B1 - 2.*A0 + 4.*A1
  U2 = XK*B2
  TEST = ABS((U2 - U1)/U2)*100.
  IF(TEST.LT.0.01) GO TO 300
  IF(J.GT.10) GO TO 200
  J = J + 1
  B1 = B2
  A0 = A1
  U1 = U2
  GO TO 10
C
200 WRITE(6,9001) Z,U1,U2
300 XN(6) = XN(6) - U2*TFAC*EFAC
9001 FORMAT(7 HYDROGEN CALCULATION DID NOT CONVERGE?4X,?Z = ?F6.1,4X,?U
* 1 = ?E12.4,4X,?U2 = ?E12.4)
  RETURN
  END

```

(FOR,IS FX,FX

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FUNCTION FX(X)

COMMON /BLK2/ AH, XN11, T11, Z11, XMH

COMMON /BLK3/ TINF, RAD, XL

DATA R/0.0540664/ G/0.0010137/

DATA AI/3.305E+21/ BI/0.5/ Z10/120./T0/273.15/ PHI/7.2E+11/

DATA T10/360./

C

E = (X - Z11)*(RAD + Z11)/(RAD + X)

EE = (X - Z10)*(RAD + Z10)/(RAD + X)

T = TINF - (TINF - T10)*EXP(-XL*EE)

C

C

TFACT = (T/T11)**(1. + AH + B*XMH)

EFACT = EXP(G*XMH*E)

IF(X,LE,240.)

* XNT = 6.8503216737E+01 - X*(4.679689977E-01 - X*(2.790152461E-0

* J - X*(8.032792295E-06 - X*8.911075174E-09)))

IF((X,GT,240.) .AND. (X,LE,340.))

* XNT = 4.94773235E+01 - X*(1.219152248E-01 - X*(4.184518744E-04

* - X*(7.806663756E-07 - X*5.708566435E-10)))

IF((X,GT,340.) .AND. (X,LE,440.))

* XNT = 4.520087318E+01 - X*(6.7935462E-02 - X*(1.626498857E-04 -

* X*(2.41150338E-07 - X*1.435244756E-10)))

IF(X,GT,440.)

* XNT = 6.2074742E+01 - X*(2.11377105E-01 - X*(6.185501048E-04 -

* X*(8.83039015E-07 - X*4.811931816E-10)))

XNT = EXP(XNT)

C

DFACT = (AI/XNT)*(T/T0)**BI

C

FX = TFACT*EFACT*PHI/DFACT

FX = FX*1.E+03

C

RETURN

END